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Climate and work load both interact with individual characteristics in determining the human heat stress response

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Heat exposure data from comparable heterogeneous subject groups (large variations in $\dot{V}O_{2\,max}$, mass, body surface area (A_{du}), fat content, A_{du}/mass ratio) who worked on a cycle ergometer at a load relative to their $\dot{V}O_{2\,max}$ (RL) in a cool (CO; 21°C, 50%rh), warm humid (WH; 35°C, 80%) and a hot dry (HD; 45°C, 20%) environment (n=24) or who worked at a fixed load (FL; 60W) in a WH (n=27) and a HD (n=30) climate, were analysed for the interaction of individual characteristics with climate type and work load. Exposures lasted 75 to 90 minutes for different conditions (constant within each condition).
The observed results can be explained by a model, in which heat production and heat dissipation capacities are correlated with the subjects $\dot{V}O_{2\,max}$, the internal heat liberation is based on metabolic rate, heat loss capacity is determined by the climate, body mass acts as a heat sink and skin fat layers only exert an insulative effect at low blood perfusion rates. This study showed, that effects of individual characteristics on human heat stress response cannot be interpreted without taking into consideration the heat transfer properties of the climate used and the metabolic heat load resulting from the type of workload.

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Gegevens uit verschillende experimenten m.b.t. de hitterespons van vergelijkbare heterogene groepen proefpersonen (verschillend in $\dot{V}O_{2\,max}$, massa, lichaamsoppervlak (A_{du}), vetgehalte, A_{du}/massa ratio) werden verzameld en integraal geanalyseerd. Het betrof experimenten waarin de proefpersonen op een fietsergometer arbeid verrichtten op een vast percentage van hun maximaal vermogen (RL, tot 45% $\dot{V}O_{2\,max}$) in een koel (CO; 21°C, 50%rh), warm vochtig (WH; 35°C, 80%) of heet droog (HD; 45°C, 20%) klimaat (n=24) of op een vaste belasting (FL, 60 Watt) in een WH (n=27) of HD (n=30) klimaat. De fysiologische reacties werden geanalyseerd op de interactie van de invloed van individuele kenmerken van de proefpersonen met het klimaattype en het soort arbeidsbelasting. Blootstellingen duurden 75 tot 90 minuten (constant per experiment). Binnen de proefpersoongroepen was $\dot{V}O_{2\,max}$ niet onafhankelijk van massa en A_{du}, maar het vet percentage was dat wel.
Hoewel $\dot{V}O_{2\,max}$ en massa sterk correleerden, liet de rectaal temperatuur (T_{re}) verschillende relaties met deze parameters zien. T_{re} correleerde negatief met massa (hoe zwaarder, hoe koeler) in alle condities. $\dot{V}O_{2\,max}$ daarentegen correleerde wel negatief in de meeste condities, maar correleerde positief met T_{re} in de WH-RL conditie (hoge aërobe fitness, hoge T_{re}). Als $\dot{V}O_{2\,max}$ voor het massa effect wordt gecorrigeerd, ($\dot{V}O_{2\,max}$/kg) dan wordt de positieve correlatie met T_{re} in WH-RL zelfs nog sterker. Dus, als de warmteafgiftecapaciteit gelimiteerd is (zoals in WH), bepaalt de absolute warmteproduktie het eindniveau van T_{re} en niet de grotere efficiency in warmteafgifte die geassocieerd wordt met een hoge $\dot{V}O_{2\,max}$. Massa werkt als een passieve warmtecapaciteit in alle condities. Het vetpercentage heeft alleen een effect op T_{re} in het CO klimaat. Alleen dan, t.g.v. de lage huiddoorbloeding, heeft vet een isolerend effect. In omstandigheden met hogere huiddoorbloeding werkt de doorbloeding als een kortsluiting van de isolerende vetlaag.
In tegenstelling tot eerdere publikaties uit diverse bronnen, had A_{du}/massa een positieve correlatie met T_{re} voor alle condities. Voor de gebruikte condities is grote massa en A_{du} blijkbaar van groter voordeel voor de fysiologische hittebelasting dan dat een hoge verhouding van beide dat is.
De hartslagfrequentie respons in de verschillende condities is sterk gerelateerd aan het arbeidsniveau t.o.v. het individuele maximum en vertoont slechts beperkte eerste orde effecten van andere individuele parameters. Reacties in huiddoorbloeding, bloeddruk en perifere vaatweerstand, evenals in zweetproduktie, vertoonden geen verschillen tussen condities in hun relatie met inter-individuele verschillen.
De gevonden relaties kunnen worden verklaard met een model waarin de aërobe fitness van de persoon de maximale warmteproduktie en de warmteafgiftecapaciteit bepaalt, het metabolisme de intern vrijkomende warmte, het klimaat de werkelijke warmteafgifte, de massa de warmteopslagcapaciteit en het vetgehalte de isolatie tussen lichaamskern en huid, zij het dat dat laatste alleen bij lage huiddoorbloeding een effect heeft.
Deze studie laat zien dat de effecten van individuele kenmerken op de fysiologische reactie op warmte niet kunnen worden geïnterpreteerd zonder rekening te houden met de warmtetransport eigenschappen van het gebruikte klimaat en het energieverbruik t.g.v. het soort inspanning.

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Institute: TNO Human Factors Research Institute
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SUMMARY

Heat exposure data from comparable heterogeneous subject groups (large variations in $\dot{V}O_{2\,max}$, mass, body surface area (A_{du}), fat content, A_{du}/mass ratio) who worked on a cycle ergometer at a load relative to their $\dot{V}O_{2\,max}$ (RL) in a cool (CO; 21°C, 50%rh), warm humid (WH; 35°C, 80%) and a hot dry (HD; 45°C, 20%) environment (n=24) or who worked at a fixed load (FL; 60W) in a WH (n=27) and a HD (n=30) climate, were analysed for the interaction of individual characteristics with climate type and work load. Exposures lasted 75 to 90 minutes for different conditions (constant within each condition). Within subject groups, $\dot{V}O_{2\,max}$ was not independent of body mass and A_{du}, but body fat content was.

Although $\dot{V}O_{2\,max}$ and mass were highly correlated, rectal temperature (T_{re}) showed different relations with these parameters. T_{re} was negatively correlated with mass (the heavier, the cooler) in all conditions. $\dot{V}O_{2\,max}$ however, though negatively correlated with T_{re} in most climates, was positively correlated with T_{re} in the WH-RL condition (high aerobic fitness, high T_{re}). When $\dot{V}O_{2\,max}$ was corrected for mass, the positive relation between $\dot{V}O_{2\,max}$/kg and T_{re} in WH-RL was even stronger. Thus, when heat loss is limited as in WH, absolute heat production (for RL related to $\dot{V}O_{2\,max}$) determines the final level of T_{re} and not the greater heat loss efficiency associated with high $\dot{V}O_{2\,max}$. Mass on the other hand acts as a passive heat sink in all the tested conditions. Body fat content only showed an effect on T_{re} in the CO condition. Only then, at low skin blood flows (measured through forearm blood flow; FBF), the insulative effect of fat is present. In other conditions with higher FBF, the blood flow short-circuits the fat thermal resistance. Contrary to other publications from various sources, A_{du}/mass showed a positive correlation with T_{re} for all conditions used. For the conditions used, a higher surface area and heat capacity (mass) apparently reduce heat strain more then a large ratio of the two.

The heart rate response to the different conditions is strongly related to the relative work load, and shows only minor effects of other individual characteristics. Responses in FBF, Mean Arterial Pressure (MAP) and Forearm Vascular Conductance (FVC), as well as in

sweat rate did not show differences in their relation with individual characteristics between conditions.

The observed results can be explained by a model, in which heat production and heat dissipation capacities are correlated with the subjects $\dot{V}O_{2\,max}$, the internal heat liberation is based on metabolic rate, heat loss capacity is determined by the climate, body mass acts as a heat sink and skin fat layers only exert an insulative effect at low blood perfusion rates. This study showed, that effects of individual characteristics on human heat stress response cannot be interpreted without taking into consideration the heat transfer properties of the climate used and the metabolic heat load resulting from the type of workload.

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Soesterberg

Klimaat en werkbelasting beïnvloeden beide de individuele karakteristieken bij het bepalen van de menselijke reactie op hittebelasting

G. Havenith, J.M.L. Coenen en J.A. Kistemaker

SAMENVATTING

Gegevens uit verschillende experimenten m.b.t. de hitterespons van vergelijkbare heterogene groepen proefpersonen (verschillend in $\dot{V}O_{2\,max}$, massa, lichaamsoppervlak (A_{du}), vetgehalte, A_{du}/massa ratio) werden verzameld en integraal geanalyseerd. Het betrof experimenten waarin de proefpersonen op een fietsergometer arbeid verrichtten op een vast percentage van hun maximaal vermogen (RL, tot 45% $\dot{V}O_{2\,max}$) in een koel (CO; 21°C, 50%rh), warm vochtig (WH; 35°C, 80%) of heet droog (HD; 45°C, 20%) klimaat (n=24) of op een vaste belasting (FL, 60 Watt) in een WH (n=27) of HD (n=30) klimaat. De fysiologische reacties werden geanalyseerd op de interactie van de invloed van individuele kenmerken van de proefpersonen met het klimaattype en het soort arbeidsbelasting. Blootstellingen duurden 75 tot 90 minuten (constant per experiment). Binnen de proefpersoongroepen was $\dot{V}O_{2\,max}$ niet onafhankelijk van massa en A_{du}, maar het vet percentage was dat wel.
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In tegenstelling tot eerdere publikaties uit diverse bronnen, had A_{du}/massa een positieve correlatie met T_{re} voor alle condities. Voor de gebruikte condities is grote massa en A_{du} blijkbaar van groter voordeel voor de fysiologische hittebelasting dan dat een hoge verhouding van beide dat is.
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Deze studie laat zien dat de effecten van individuele kenmerken op de fysiologische reactie op warmte niet kunnen worden geïnterpreteerd zonder rekening te houden met de warmtetransport eigenschappen van het gebruikte klimaat en het energieverbruik t.g.v. het soort inspanning.

1 INTRODUCTION

Large differences between individuals in their response to exercise in the heat have been described in the literature (Kenney, 1985; Wenzel et al., 1989; Havenith et al., 1995a,b). These differences can in part be ascribed to differences in specific personal characteristics of these subjects. Research on the effect of different characteristics as age, gender, body size, adiposity and aerobic fitness has been extensive and resulted in a widely accepted notion that aerobic fitness, adiposity and anthropometrics are the main determinants for heat stress response and that most effects observed in relation to age and gender differences are really due to concomitant differences in the first three mentioned parameters (Kenney & Havenith, 1993; Havenith et al., 1995a,b; Pandolf et al., 1988). The experimental approach differed between studies. Most studies used the classical approach of studying a difference in one parameter at the time (Frye & Kamon, 1981; Anderson & Kenney, 1987; Pandolf et al., 1988), using T-tests or analysis of variance as statistical tool. Others (Havenith & Van Middendorp, 1990; Havenith et al., 1995a,b) used an approach in which they submitted a heterogeneous subject group to heat stress and analysed the results by multiple regression techniques. The latter allowed the determination of the relative importance of different parameters in relation to each other. These studies have been performed with different types of metabolic loads: fixed work loads (FL) for all subjects (Havenith et al., 1995a,b), or work loads relative (RL) to the subjects individual maximum (Havenith & Van Middendorp, 1990), in combination with different climate paradigms: Cool (CO), Warm-Humid (WH) and Hot-Dry (HD) (all combinations except CO-FL and HD-FL). These studies showed that the widely believed concept that body core temperature is determined by workload expressed as $\%\dot{V}O_{2\,max}$ (Saltin & Hermansen, 1966; Åstrand, 1960) and sweat loss by absolute heat (work) load (Drinkwater & Horvath, 1979), was only partially supported by the results. For both variables, (other) individual characteristics were shown to contribute too (Havenith et al., 1995b).

The present study will add data for work at a fixed load in a hot-dry climate (HD-FL) to the above mentioned data sets. With these additional data available, differences related to climate type and work load can be studied. The question to be answered in this report is therefore how the relation between individual characteristics and heat stress response is influenced by the type of work load and the type of climate. Further, an attempt will be made to relate the results to a qualitative model of human heat exchange with the environment.

2 METHODS

The main purpose of this report is to present the combined data of five different experiments covering combinations of two parameters: climate type and work type (Table I). This methods section will describe the procedures used in the HD-FL experiment, as that has not been described before.

Overall, two work types were used in the experiments: FL (60 Watts on a reclining cycle ergometer, equal for all subjects) and RL (3 subsequent 30 min. periods at 15, 25 and 45% $\dot{V}O_{2\,max}$). Three subject groups were involved. One group participated in all relative load tests (within subjects, CO, WH and HD). Another participated in the FL, WH condition and a third group in the FL, HD condition.

All groups used were selected using the same criteria to allow between groups comparisons.

Table I Overview of subject groups used in different combinations of climate type and type of work load. (Group 1: Havenith & Van Middendorp, 1990; Group 2: Havenith et al., 1995a,b; Group 3: this report.)

climate: work type:	Cool (CO: 21°C, 50%)	warm, humid (WH: 35°C, 80% rh)	hot dry (HD: 45°C, 20% rh)
Relative Load (RL)	Group 1 (n=24)	Group 1 (n=24)	Group 1 (n=24)
Fixed Load (FL)	–	Group 2 (n=27)	Group 3 (n=30)

Four of these experiments (CO-RL, WH-RL, HD-RL and FL-WH) were described elsewhere (Havenith & Van Middendorp, 1990, Havenith et al., 1995a,b). The methods of the fifth (FL-HD) will be described here. Apart from climatic and work conditions, techniques used over all experiments were similar.

Screening: 35 subjects volunteered for the study, which was approved by the Institute's Medical Ethics Committee. Before participation in the experiment the subjects signed an informed consent and were medically screened. This included a physical examination, resting electrocardiogram (ECG), and completion of a medical history form. Each potential subject underwent a graded exercise test (GXT) on a bicycle ergometer. During the GXT, heart rate and blood pressure (via brachial auscultation) were obtained every minute. Maximally obtained oxygen uptake ($\dot{V}O_{2\,max}$) was calculated using the maximally achieved workload during the GXT (Binkhorst, 1993) and served as measure of aerobic power. Adiposity was defined as the fat percentage, measured as the sum of 4 skinfolds (Durnin & Womersley, 1974). The subjects habitual physical activity level was recorded using a questionnaire, describing their participation in exercise programs etc. (Ross & Jackson, 1990). Activity level (ACTIV) was scored on a 7 point scale, ranging from "avoid walking or exertion" (1) to "run over 10 miles/week or exercise over 3 hours/week" (7). Body surface area (A_{du}) was determined from height ($\pm$ 0.5 cm) and mass ($\pm$ 10 g) according to DuBois and DuBois (1916) and was also used to calculate the surface to mass ratio of the subjects (A_{du}/mass).

On statistical grounds [too many lean, high $\dot{V}O_{2\,max}$ subjects for a normal distribution (Havenith et al., 1995a)] 3 subjects were a priori excluded from the heat stress test (HST), leaving 32 (15 males, 17 females) HST subjects. Natural acclimatization levels of all subjects were presumed to be equal, as all tests were performed in the spring. Subjects were interviewed for possible recreational heat exposures.

Heat stress test: For the heat stress test (HST), each subject reported to the lab, changed into shorts (women also halter top) and had sensors attached (description below). Next they entered the climatic chamber controlled at an ambient and radiative temperature of 45°C, at a relative humidity of 20% and a wind speed below 0.2 $m \cdot s^{-1}$. The subjects rested for 30 minutes in a semi-reclining chair mounted behind a cycle ergometer. Next they started to perform work (60 Watt) on an electrically braked bicycle ergometer (Lode). They aimed at a cycling frequency of 60 rpm. They cycled for a period of 60 minutes, or until reaching one of the safety criteria (rectal temperature (T_{re}) > 39°C or HR > 90% of the individual maximum as determined in the GXT, or any adverse symptomology). During the period in the climatic chamber on-line measurements were made, using a Fluke data acquisition system, of the following variables: T_{re} by a thermistor (Yellow Springs Instruments, 700 series) inserted 12 cm beyond the anal sphincter; mean skin temperature, as a surface area weighted average of 4 YSI 700 series thermistors placed on the arm, upper leg, chest and back; Oxygen uptake ($\dot{V}O_2$) by analysis of expired gasses during two five minute periods (after 15 min. and after 45 min work) using a Mijnhardt Oxycon Sigma system; HR, from CM_5 lead via a recorder and oscilloscope for constant monitoring; Forearm blood flow (FBF), using venous occlusion plethysmography (Whitney, 1953), with temporary arterial occlusion of the hand and venous occlusion of the upper arm. Mean arterial blood Pressure (MAP) was determined by brachial auscultation and calculated as:

$$MAP = \frac{(2.0 \cdot \text{diastolic pressure} + \text{systolic pressure})}{3.0} \qquad \text{(Torr)}$$

Forearm Vascular Conductance (FVC) was calculated as:

$$FVC = \frac{FBF}{MAP} \qquad (\%\ \text{min}^{-1}\ \text{Torr}^{-1})$$

Sweat loss was determined by weighing subjects before and after the heat exposure. Mass loss was not corrected for metabolic and respiratory mass losses, as these were assumed to be equal for all subjects due to the fixed metabolic rate.

Data were stored at 60 second intervals. The final statistical analysis was performed using the data points collected at and averaged over the last 3 minutes of the test.

Statistics: For the statistical analysis, correlation analysis modules of the package "SYSTAT" (Wilkinson, 1990) and "STATISTICA" (1995) were used. Distributions of data were tested for normality using probability plots and skewness and kurtosis calculations. Significance levels $p<0.05$ were accepted. Outliers were determined using studentized residuals and Cook's D-statistic.

Differences between conditions were tested only for comparisons within the climate type (WH-RL vs WH-FL and HD-RL vs HD-FL) or within a work type (CO-RL vs WH-RL vs HD-RL and WH-FL vs HD-FL).

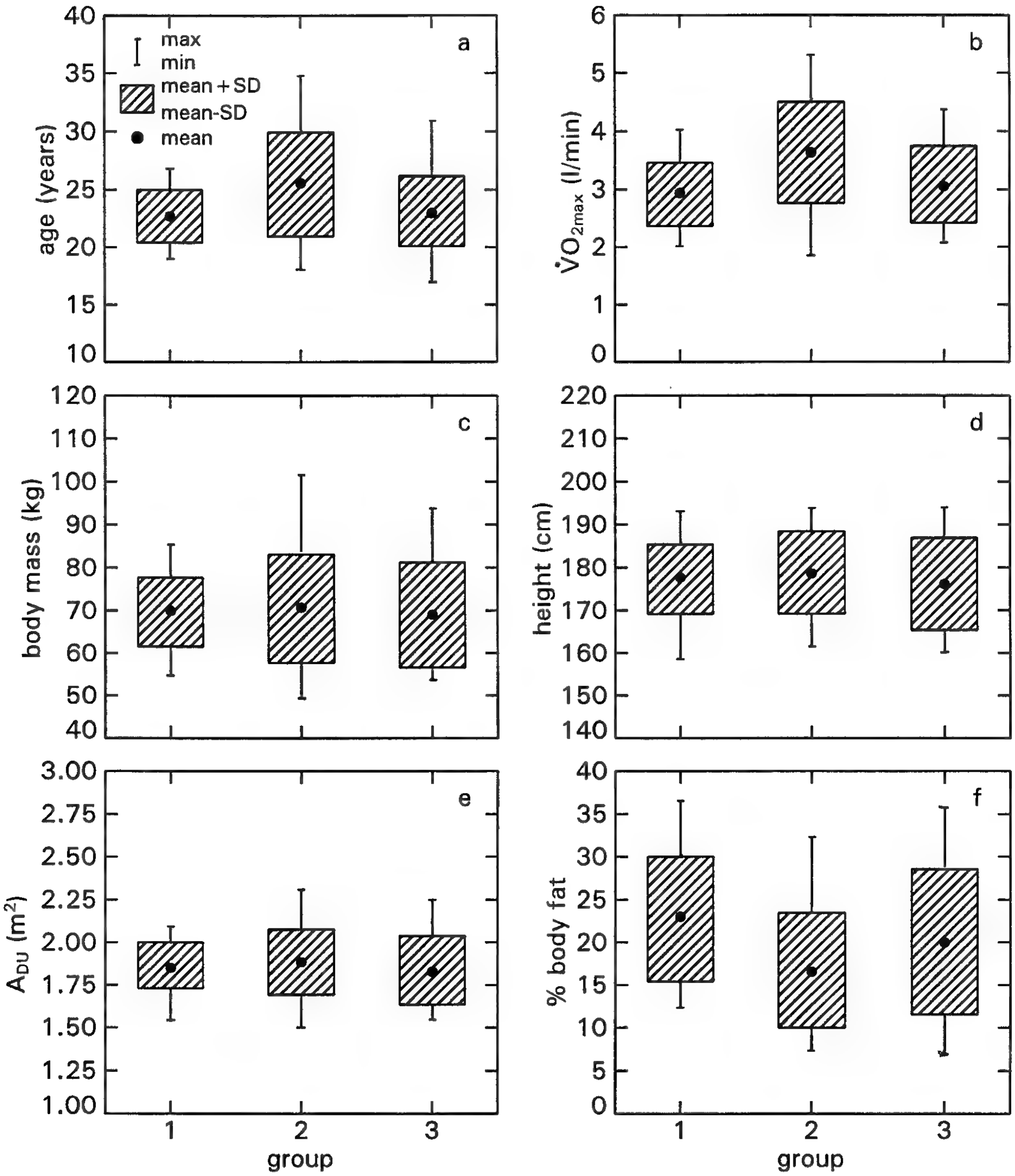

Fig. 1 Mean, standard deviation (sd), minimum and maximum values for physical and physiological characteristics of the subject groups used in the analysis. % body fat = fat percentage; A_{du} = body surface area.

In the following presentation of results, the main focus will be on the interaction between climate-work type combination on one hand and the effect of individual characteristics ($\dot{V}O_{2\,max}$, mass, A_{du} etc.) on heat stress responses on the other. Thus mainly when the relation (correlation) of the response (e.g. T_{re}) with the individual parameter differs between climate-work conditions, they will be discussed in more depth.

3 RESULTS

Of the 32 subjects participating in the experiment, only 22 were able to complete the full 90 minute period. As this would reduce the data set too much, it was chosen to use the 75 minute point as end of the test for the data analyses. 30 subjects reached this point (14 males, 16 females). Their characteristics are presented in Fig. 1, group 3, together with those of the other subject groups, mentioned in Table I. All other results will be discussed together with those of the other climate/work combinations of Table I.

Subject groups did not show any significant difference in personal characteristics, thus allowing a good comparison between groups. Though an attempt was made to minimize correlations between individual characteristics within groups by subject selection, $\dot{V}O_{2\,max}$ and mass were significantly correlated. These parameters had to be treated with caution in the analyses. Also, as can be expected, body surface area was related to mass and height. Body fat content on the other hand was not correlated with $\dot{V}O_{2\,max}$ nor with body mass, nor body surface area.

Rectal temperature

In Fig. 2a the correlation coefficients of the relation between T_{re} and $\dot{V}O_{2\,max}$ are given for the five climate/work load conditions. For the fixed work loads, significant, negative, correlations are present. For the relative loads, only the positive correlation for the WH-RL condition approaches significance ($p=.08$). This positive correlation for the WH-RL condition differs significantly from all other conditions, except from HD-RL, where it approaches significance ($p=.08$).

The relation between T_{re} and body mass is given in Fig. 2b. The relations are similar for both relative loads in the heat and also for both fixed loads in the heat. For the neutral climate the correlation was not significant. The relation of A_{du} with T_{re} is almost identical to that given for body mass.

As a positive correlation between body mass and $\dot{V}O_{2\,max}$ was present in the subject groups, it was tested whether the significances of Fig. 2a were due to the mass effect. For this purpose the correlations between Tre and relative aerobic power ($\dot{V}O_{2\,max}$/kg) were calculated (Fig. 2c). In this case, only the correlation for the WH-RL was significant [WH-FL approaches significance ($p=.07$)] and this WH-RL condition differs significantly from all other conditions.

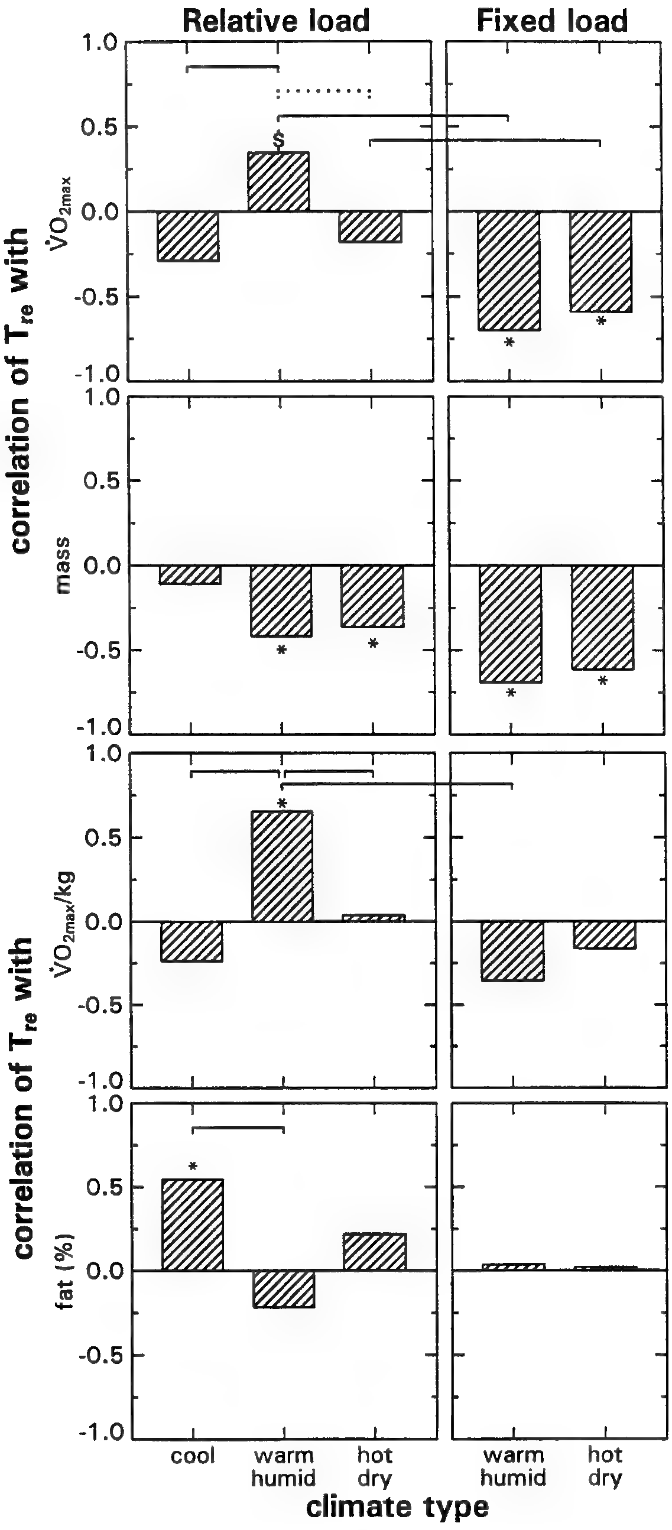

Fig. 2 Correlations of rectal temperature (T_{re}) with -a- maximal oxygen uptake ($\dot{V}O_{2\,max}$), -b- body mass, -c- maximal oxygen uptake per kg of body mass ($\dot{V}O_{2\,max}$/kg), and -d- body fat content. $*=p<0.05$; $\$=0.05<p<0.1$; lines connect conditions which are significantly different (comparison within climate or work type only; see methods); dotted line: difference at p-level: $0.05<p<0.1$.

In Fig. 2d, the relation of T_{re} with body fat content is presented. Only for the CO-RL condition this correlation is significant (positive), and significantly different from the other conditions except HD-RL.

Skin temperature

The relation between skin temperature and aerobic power ($\dot{V}O_{2\ max}$) (Fig. 3a) is similar to the relation of T_{re} with $\dot{V}O_{2\ max}$, except for the CO-RL condition. When the work load is fixed, or relative in case of the hot dry climate (p=.08), subjects with higher aerobic fitness levels have lower skin temperatures whereas for the relative load in the warm humid climate, the skin temperature is higher for subjects with higher $\dot{V}O_{2\ max}$. For the neutral climate the positive correlation between T_{sk} and $\dot{V}O_{2\ max}$ approaches significance (p=.07). The relation of T_{sk} with $\dot{V}O_{2\ max}$/kg is virtually the same as that with $\dot{V}O_{2\ max}$. The correlations of T_{sk} with body mass and A_{du} are negative (insignificant for RL) for all conditions).

The image of the relation of T_{sk} with body fat content is the reverse of that of T_{sk} with $\dot{V}O_{2\ max}$ (Fig. 3b). The CO-RL condition differs significantly from the HD-RL condition.

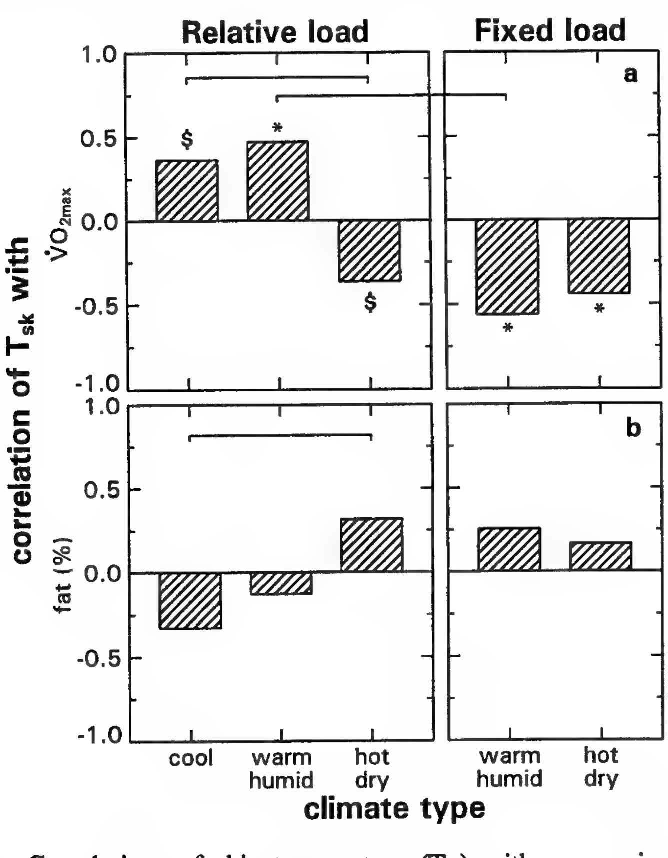

Fig. 3 Correlations of skin temperature (T_{sk}) with -a- maximal oxygen uptake ($\dot{V}O_{2\ max}$), and -b- body fat content.

Heart rate and other circulatory parameters

The correlation of $\dot{V}O_{2\,max}$ with heart rate for the different climate/work load types is given in Fig. 4. For the fixed work load, the correlation is negative and significant. For the RL conditions, no correlation between HR and $\dot{V}O_{2\,max}$ is present. No climate effect was present.

A very similar picture to Fig. 4 is present in the correlation of HR with body mass or A_{du}: strongly negative for the fixed loads, no significant correlation of mass with HR for the relative loads, and the difference between RL and FL significant. Here also no climate effect was observed.

Correlations of HR with body fat content are all not significant.

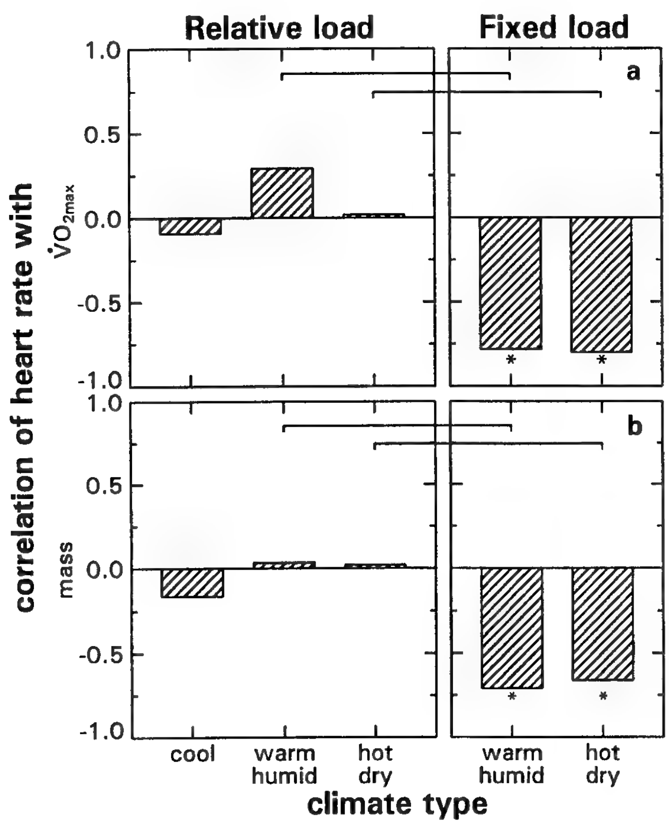

Fig. 4 Correlations of heart rate with maximal -a- oxygen uptake ($\dot{V}O_{2\,max}$) and -b- mass for the different conditions.

For all relations of other circulatory parameters (FBF, MAP and FVC) with individual parameters, differences between conditions are not significant.

Sweat rate

Body sweat rate shows a strong (positive) correlation with $\dot{V}O_{2\,max}$, A_{du} and mass. This correlation is very similar for all conditions. When sweat rate is expressed per unit of body

surface area the correlations are reduced, but most remain significant (Fig. 5a). Though the correlation is lower and not significant for the warm humid environment at the fixed load, the differences between conditions are not significant.

The correlation between sweat rate or sweat rate per unit surface area (Fig. 5b) and body fat content is insignificant for the FL conditions and significantly negative in all other.

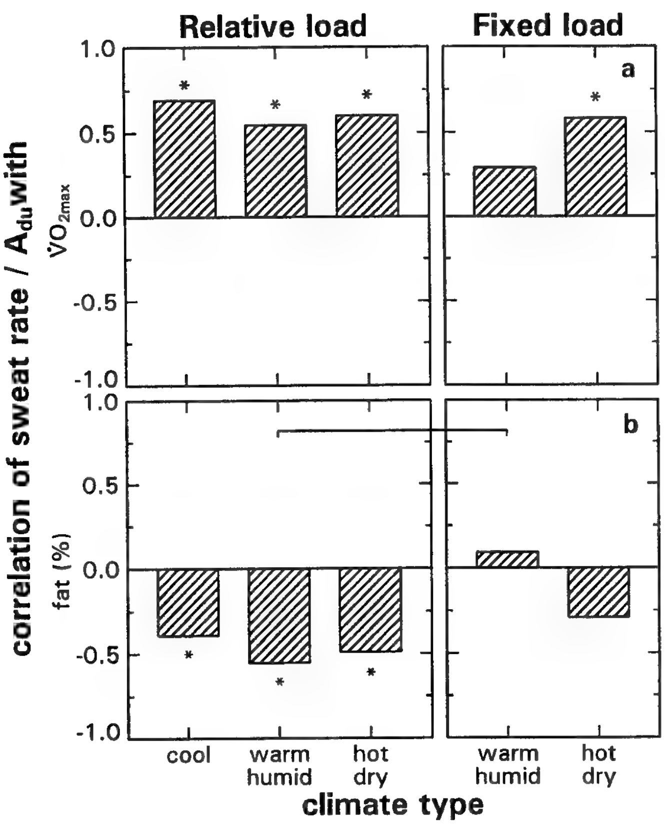

Fig. 5 Correlations of sweat rate with: -a- maximal oxygen uptake ($\dot{V}O_{2\,max}$) and -b- body fat content for the different conditions.

4 DISCUSSION

The result of the present experiment (HD-FL) will be discussed in conjunction with those of all other conditions.

Methodology

The methodology of using heterogeneous subject groups, including males and females, instead of groups matched for all but one parameter was discussed by Havenith et al. (1995a). In this type of experiments, analyses by multiple regression is used. However, for the present approach, aiming at comparison of responses over climates and work load types and their combinations, this approach was deemed to be too complex for comparison of e.g.

second or third order correlations (second and third parameters in multiple regression analysis) over different conditions. Therefore, in the present report, a comparison was made based on first order correlations between individual differences and heat stress responses.

Subject groups were chosen with a large variation in individual characteristics within each group. Both genders were included, but not analysed separately. This decision was based on conclusions of previous research (Avellini & Kamon, 1980; Frye et al., 1981, 1982; Havenith & Van Middendorp, 1990), that gender differences in thermoregulatory response are really due to differences in fitness and anthropometry. Inclusion of both genders resulted in a wider variation within the subject groups in individual characteristics.

Between the groups, mentioned in Table I, the ranges of the individual characteristics ($\dot{V}O_{2\,max}$, mass, height, fat content, age, A_{du}) as well as their mean and standard deviations, were similar and not significantly different (Fig. 1). Therefore, correlations between responses and individual parameters are valid measures for comparison over climates and work types. Experiments, though different in work load protocol and work duration, were sufficiently long to allow a development of typical (heat) stress responses.

As $\dot{V}O_{2\,max}$ and mass were significantly correlated in all data sets, these parameters had to be treated with caution in the analyses. In part, this was approached by correcting $\dot{V}O_{2\,max}$ for the mass effect, using $\dot{V}O_{2\,max}$/kg. Although $\dot{V}O_{2\,max}$ and mass were correlated, for each level of $\dot{V}O_{2\,max}$ still a large variation in masses was present. This explains why it was possible that different effects for these two parameters were observed, as will be discussed below. Body fat content on the other hand was not correlated with $\dot{V}O_{2\,max}$ or with body mass, or A_{du}, due to selection of subjects within the test groups (Havenith et al., 1995b).

Rectal temperature

A clear difference in the correlation coefficients of the relation between T_{re} and $\dot{V}O_{2\,max}$ or $\dot{V}O_{2\,max}$/kg for the five climate/work load conditions was observed (Fig. 2). For the relative work loads, where according to literature (Saltin & Hermansen, 1966; Åstrand, 1960) one would expect no correlation between T_{re} and $\dot{V}O_{2\,max}$, or $\dot{V}O_{2\,max}$/kg, significant correlations are still present. Furthermore these differ between different climate types. Where small negative correlations are present for the neutral and hot climate a significant positive correlation is observed for the warm humid climate. The higher the subject's aerobic fitness, the higher the T_{re}.

For the fixed work loads, a negative correlation exists in both cases for the correlation with $\dot{V}O_{2\,max}$, which becomes just insignificant for the WH-FL condition ($p=.07$) and insignificant for the HD-FL condition when aerobic fitness is expressed as $\dot{V}O_{2\,max}$/kg.

These findings can be explained as follows: For the relative work load, the heat liberated in the body is dependent on the subjects $\dot{V}O_{2\,max}$ (assuming equal work efficiencies). The subject's heat dissipation capabilities are also related to his $\dot{V}O_{2\,max}$ (Avellini et al., 1982, Yoshida et al., 1995). Thus when these two relations are equally strong, no correlation should be found between T_{re} and $\dot{V}O_{2\,max}$ for relative work loads. This is the case for the

neutral and the hot-dry climate. In the warm humid climate, however, the heat dissipation from the body is not limited by the body's capacity, but by the climate conditions. Due to the high humidity the evaporative capacity is then strongly reduced. In this case the subjects with a high $\dot{V}O_{2\,max}$ will have a high work load and heat production in the body, but they are unable to dissipate substantially more than less fit subjects due to climatic restrictions. Thus T_{re} will rise with heat production and consequently relative to $\dot{V}O_{2\,max}$. For the fixed work load on the other hand, the heat liberation in all subjects is equal. Any advantage in heat loss capacity of fitter subjects will thus become visible as a reduced T_{re}.

The relation between T_{re} and body mass as presented in Fig. 2 shows that the correlations are similar for both relative loads in the heat and also for both fixed loads in the heat. For the neutral climate the correlation was not significant. Thus in general one might say that the bigger the body (larger mass, but also larger A_{du}), the lower the increase in T_{re}. However, the interpretation of this finding is critical as positive correlations between body mass and $\dot{V}O_{2\,max}$ were present in the subject groups. Thus one might argue that the mass effect is not due to e.g. the higher heat storage capacity which is concomitant with high mass, but acts through the mechanisms associated with the concomitant high $\dot{V}O_{2\,max}$, or vice versa. Surprisingly, however, the relations of mass and $\dot{V}O_{2\,max}$ with T_{re} are not similar for all conditions: they are opposite in sign for the WH-RL condition, but similar in all others. This can be explained as follows: in general. the effect of $\dot{V}O_{2\,max}$ and body mass on T_{re} work in the same direction: Where the aerobic fitness level is related to an active influence on heat dissipation (higher sweat sensitivity etc., resulting in a negative correlation with T_{re}), body mass has (for the cycling exercise used) a more passive effect: when heat accumulates in the body, the rise in T_{re} will be slower when heat capacity of the body ($\approx$mass) and body surface area (A_{du}, cooling area) are higher. When the climate limits heat loss, a big mass still will imply a high heat storage capacity and thus the correlation of T_{re} with mass remains negative. However, in that same climate, as described above, the high $\dot{V}O_{2\,max}$ will not be of advantage when working at a relative load. Thus, the latter effect on T_{re} will become opposite (positive) in sign compared to the effect of mass.

This difference between conditions is strongly visualized in Fig. 2c, where the correlations of T_{re} with the ratio of aerobic power to body mass are presented. The negative effect of a high aerobic fitness for heat strain in the WH-RL condition is pronounced.

Body fat was for most data sets not or minimally correlated with $\dot{V}O_{2\,max}$ or mass, due to selection of subjects on this point (Havenith, 1995a,b). For the correlation of T_{re} with body fat content, only the relative load in the CO climate shows a significantly different correlation coefficient from the other conditions. Where in the CO climate there is a positive correlation between fat content and T_{re}, there is no significant first order correlation in the other climates. If one considers fat as a potential insulative layer, this insulating effect will be strongly dependant on the blood perfusion of this layer (Burse, 1979; Havenith, 1985). In the CO climate, measured forearm blood flows, taken as representative for skin blood flow, were low (maximum 7 ml/100ml/min). In this case fat could exert its insulating effect, resulting in higher body temperatures for the fatter subjects. For the warmer climates, where FBF's where substantially raised (averages 14 to 21 ml/100ml/min), this shortcut for heat transport reduced the active heat resistance of the fat layer to virtually zero and thus resulted

in insignificant effects of body fat on T_{re}. The latter finding is in accordance with observations of Burse (1979), who observed that gender differences due to differences in fat layers were absent for exercise in the heat.

It should be noted that body fat in studies using weight bearing exercise (treadmill) may exert an effect on heat stress response through its passive mass which has to be carried by the subject, which is different from the insulating effect. Also the specific heat of adipose tissue, in which water content is low, is about half that of the fat-free mass. Therefore, a given heat load per kg body weight will cause higher temperature elevations in the obese than in lean subjects (Bar-Or et al., 1969).

While A_{du} as well as mass both show a negative correlation with T_{re}, the surface to mass ratio of subjects (A_{du}/mass) shows a positive relation. This is strongest for the FL conditions and slightly lower for the RL conditions. The higher the surface to mass ratio (the smaller the subject) the higher also T_{re}. This observation is consistent over all conditions in the current experiment (all significant, except the cool climate). Apparently, for cycling exercise, the absolute value of mass and A_{du} (heat storage capacity and cooling surface) is more beneficial in reducing heat strain than a high ratio of the two (high cooling surface area for a low heat producing mass) is.

Though supported by earlier results (Austin & Ghesquiere, 1976), this finding is exactly opposite from most earlier studies on this subject (Shvartz et al., 1973; Shapiro et al., 1980; Austin & Lansing, 1986) where a negative correlation between A_{du}/mass and T_{re} for warm humid climates or work in vapour barrier clothing and no correlation for dry climates was observed. These findings formed part of the basis for the explanation of male-female differences in heat stress response (females smaller and thus higher A_{du}/mass). Re-evaluating the data of those studies showed that a methodological problem might be present in these experiments. They all used a treadmill walking protocol, with fixed speed and grade. Thus the metabolic rate of the subjects was directly dependent on their body mass and thus also on A_{du}/mass. The bigger the subject, the more heat was liberated. When the climate prevents efficient cooling, more heat accumulates in the body. Though bigger subjects have a higher storage capacity, the higher heat production apparently had a stronger effect, resulting in a higher T_{re} for bigger (low A_{du}/mass) versus smaller (high A_{du}/mass) subjects. Thus in our opinion, the negative correlation of A_{du}/mass with T_{re} observed in those walking type experiments, was actually due to differences in metabolic rate between different A_{du}/mass groups. Shvartz et al. (1973) already pointed at this alternative explanation of their findings.

Classical descriptions of inter-species differences in surface to mass ratio on heat tolerance may not apply to within species differences, as shown here.

Skin temperature

The relation between skin temperature and aerobic fitness ($\dot{V}O_{2\,max}$) reflects the same mechanisms as the relation of T_{re} with $\dot{V}O_{2\,max}$ (Shapiro, 1980). When the work load is fixed, or relative in case of the hot dry climate, fitter subjects have lower skin temperatures (higher/more efficient evaporation due to higher sweat production and better sweat distribu-

tion) whereas for the relative load in the warm humid climate, where sweat efficiency related to high $\dot{V}O_{2\,max}$ is not really effective, the skin temperature is higher for subjects with higher $\dot{V}O_{2\,max}$ and thus higher heat loads. Interestingly T_{sk} also may be positively correlated ($p=.07$) with $\dot{V}O_{2\,max}$ for the CO climate. Absolute T_{sk} is much lower in this case than for the heat exposures (29.5 versus 36−38°C) and the positive correlation in this case is most likely a reflection of the actually observed higher FBF for fitter subjects in this case. Also for the CO-RL condition, contrary to the HD climate where skin temperature is higher with higher fat content, T_{sk} is lowest when the skin fat layer is thickest. Apparently, though the skin fat layer does not have an insulator effect on body core temperature in the heat, it has sufficient effect to show a trend of hotter skin in dry heat and cooler skin in cool environments with increasing fat content. Though the difference between these conditions is significant, both effects separately only approach significance.

Heart rate

Heart rate represents, besides the actual work load, also the thermoregulatory effect of increasing skin blood flow during body temperature increase.

The correlation of $\dot{V}O_{2\,max}$ with heart rate for the different climate/work load types, as presented in Fig. 4 shows that correlations are insignificant except for the fixed work load, where the correlation is negative. This correlation is not unexpected (Smolander et al., 1987). The higher the subjects aerobic fitness, the lower that fixed work load will be in terms of the load on the person relative to his or her personal maximum. Thus, also the higher the $\dot{V}O_{2\,max}$ the lower the heart rate. At the relative work load, heart rates are expected to be equal for all subjects, assuming that they have similar maximal heart rates. Inspection of the data set did show a variability in maximal HR, but this was not related to $\dot{V}O_{2\,max}$. Equal HR are indeed the case for the neutral and the hot dry climate. Only a small but insignificant positive correlation is present in the WH-RL condition. This is most likely related to the higher core temperatures of the fitter subjects in this situation, which necessitates a stronger thermoregulatory reaction, stronger skin blood flow, and thus a higher additional increase in heart rate.

The correlation of HR with body mass is strongly negative for the fixed loads, which reflects the correlation of mass with $\dot{V}O_{2\,max}$. The higher the mass, the higher the $\dot{V}O_{2\,max}$. Also, the equal heat production for all subjects at a fixed load is distributed over a heat sink which is directly related to body mass. Thus, with a big mass T_{re} can remain lower and thus also the thermoregulatory increase in HR can remain lower too. For the relative loads, no significant correlation of mass with HR is present, supporting the explanation given above.

Other circulatory parameters

The relationship of FBF, MAP and FVC with $\dot{V}O_{2\,max}$, mass and body fat, did not show significant differences between the climate types and work load types.

Absolute levels of MAP for the warm and hot climate types are lower than for the CO climate, reflecting the lowered peripheral vascular resistance, which is not completely

compensated by increased cardiac output (Smolander et al., 1987). In the CO-RL condition, the correlation of FBF and FVC with body fat is zero. Thus the above described higher T_{re} with high fat content in that condition is not due to a lower FBF or FVC in subjects with high fat contents but must be related to the insulative effect of the fat layer at the observed low FBF's.

Sweat rate

Body sweat rate (per unit of surface area) shows a distinct correlation with $\dot{V}O_{2\,max}$, but this is very similar for all conditions (Fig. 5). Though the correlation seems lower for the warm humid environment at the fixed load, these differences are not significant. Thus whether work load is fixed or related to the $\dot{V}O_{2\,max}$, a positive correlation of sweat production with $\dot{V}O_{2\,max}$ is present. Fitter people produce more sweat in all the conditions. The concept that sweat rate is related to absolute metabolic load or work rate (Drinkwater & Horvath, 1979) may hold true, but apparently there is sufficient variance in the data which still can be attributed to the individuals $\dot{V}O_{2\,max}$.

General discussion

In order to understand the findings in terms of physiological and biophysical mechanisms, one may try to develop a general model of these responses.

If one takes the body as a box with a certain mass, this mass determines heat storage capacity as well as the body surface (=heat loss) area. Maximal heat production levels (muscle mass) as well as heat dissipation mechanisms (sweat production, sweat evaporation efficiency) are related to $\dot{V}O_{2\,max}$ (Avellini et al., 1982, Yoshida et al., 1995) and, for a normal population where $\dot{V}O_{2\,max}$ and mass are correlated, thus indirectly to mass too.

For the cycling exercise used, heat production in the FL studies is equal over masses, and as $\dot{V}O_{2\,max}$ is strongly related to mass, heat production is roughly equivalent to mass in the RL studies. Body fat and skin blood flow can be seen as parallel resistances between core and skin. Body fat is therefore only active as insulator when skin blood flow is low (high parallel resistance), thus in cool climates.

This simple model is consistent with the findings: At equal heat productions (FL), whether evaporative heat loss is limited (WH) or not (HD), a high heat loss capacity (high surface area, high $\dot{V}O_{2\,max}$) combined with a high heat storage capacity (mass) will result in lower strain (lower body temperatures, heart rates) for subjects with a high mass and/or a high $\dot{V}O_{2\,max}$, as observed.

When heat production is related to maximal aerobic capacity (RL), this is balanced by the heat storage capacity and heat loss capacity which are also related to $\dot{V}O_{2\,max}$ and mass. Thus when sweat evaporation is not limited (HD, CO), one expects (Saltin & Hermansen, 1966; Åstrand, 1960) and observes equal increases in body temperature for different masses and aerobic fitness levels. When however heat losses are limited by the climate (WH), the higher efficiency in heat loss for the aerobically fitter subjects cannot be realized. The higher heat

production will in this case directly result in higher body temperatures for subjects with a high $\dot{V}O_{2\,max}$. Within these groups of low and high aerobic fitness, the subjects fat content affects core temperature increases only in the cool climate where skin blood flow is low.

In other conditions then studied here (e.g. walking at a certain speed), an increase in fat content has also indirect effects: it increases the (passive) mass that has to carried and thereby metabolic rate.

This study shows, that effects of individual characteristics on human heat stress response cannot be defined without taking into consideration the heat transfer properties of the climate used and the metabolic rate resulting from the type of workload. Taking this into consideration, seemingly contradictory results from different studies can be explained using a single model.

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Climate and work load both interact with individual characteristics in determining the human heat stress response

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

Heat exposure data from comparable heterogeneous subject groups (large variations in $\dot{V}O_{2\,max}$, mass, body surface area (A_{du}), fat content, A_{du}/mass ratio) who worked on a cycle ergometer at a load relative to their $\dot{V}O_{2\,max}$ (RL) in a cool (CO; 21°C, 50%rh), warm humid (WH; 35°C, 80%) and a hot dry (HD; 45°C, 20%) environment (n=24) or who worked at a fixed load (FL; 60W) in a WH (n=27) and a HD (n=30) climate, were analysed for the interaction of individual characteristics with climate type and work load. Exposures lasted 75 to 90 minutes for different conditions (constant within each condition).
The observed results can be explained by a model, in which heat production and heat dissipation capacities are correlated with the subjects $\dot{V}O_{2\,max}$, the internal heat liberation is based on metabolic rate, heat loss capacity is determined by the climate, body mass acts as a heat sink and skin fat layers only exert an insulative effect at low blood perfusion rates. This study showed, that effects of individual characteristics on human heat stress response cannot be interpreted without taking into consideration the heat transfer properties of the climate used and the metabolic heat load resulting from the type of workload.

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